UNDULATOR-BASED POSITRON SOURCE FOR CLIC*

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Abstract

A model has been created in Geant4 [1] to simulate the key elements of an undulator-based positron source for CLIC: the goal is to consider such a source as an alternative to the present baseline concept. The parameters of the undulator and capture device need to be adjusted to cover a range of operating scenarios. We report the results of calculations for two specific operating scenarios, for the rate of positron production, positron polarisation, and capture efficiency.

INTRODUCTION

CLIC is a high-energy linear collider designed for precision studies of the Higgs boson and other new physics phenomena. Electrons and positrons will be collided at centre of mass energy up to 3 TeV. In order to achieve the specified luminosity, CLIC will need of order 10^{14} positrons per second; for some of the planned studies, the positron beam will need to be polarised. The required rate of positron production is a factor ∼60 greater than any previous source, such as the SLC at SLAC. So far, three schemes have been considered [2] for the positron source: a conventional source, a source based on Compton back-scattering [3], and an undulator-based source. In this paper, we will consider the undulator scheme, and calculate key performance properties, including the achievable production rate and polarisation. The system we consider, from the undulator to the capture optics, is based on the present baseline for ILC [4, 5, 6] except that we are using an adiabatic matching device (AMD) for positron capture, to maximise the positron yield.

Key parameters for an undulator-based positron source include the electron beam energy, and the undulator period and field strength. These parameters determine the photon flux and energy spectrum incident on the target. The design of the system is complicated by the fact that the collider will be built to operate initially at 500 GeV centre of mass energy, then upgraded to 3 TeV by increasing the accelerating gradient. The dependence of the photon properties on electron beam energy may make it unfeasible to operate with a given undulator at a fixed location over such a wide range of electron energies. Therefore, we need to consider practical changes to the system that will allow an undulator-based source to operate over the envisaged range of collider parameters. As an initial step towards optimization of the design, we consider two scenarios:

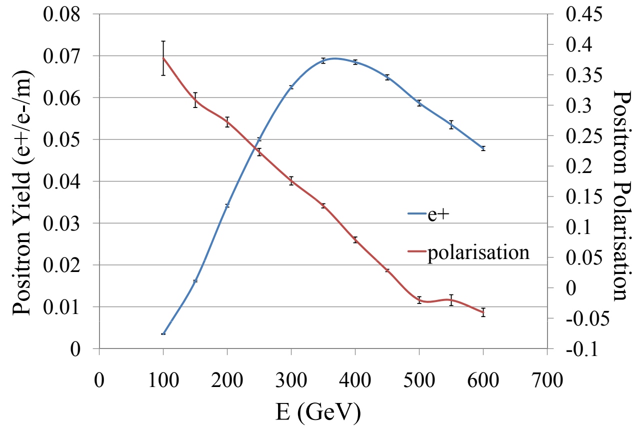

Figure 1: Positron yield (per meter of undulator) and polarisation as functions of electron beam energy. The error bars show the statistical uncertainty in numerical modelling.

1. fixed undulator parameters, with undulator at different positions in the linac, depending on the center of mass energy;
2. fixed undulator position, but different parameters, depending on the centre of mass energy.

FIXED UNDULATOR PARAMETERS

With fixed undulator period and field strength, the total number of photons emitted per unit length is independent of the electron beam energy; however, the photon energy (in particular, the first harmonic cut-off) will increase, which will help to produce more positrons. In principle, the length of the undulator can be reduced with increasing electron energy. However, the capture device after the target can only capture positrons within a certain angle and energy acceptance window, and this leads to a reduction in the number of positrons delivered to the (pre)damping rings, as the electron energy is increased above a certain value. Fig. 1 shows the positron yield and polarisation, as functions of the electron energy from 100 GeV to 600 GeV: fixed undulator period and field strength are assumed.

Electron Beam Energy

First stage From Fig. 1, we can see that for electron energy up to about 350 GeV, increasing the electron energy increases the positron yield, and potentially allows for a shorter undulator. Placing the undulator at the end of the linac would, in the first stage of CLIC operations, provide a positron yield of about 0.05 positrons per electron per

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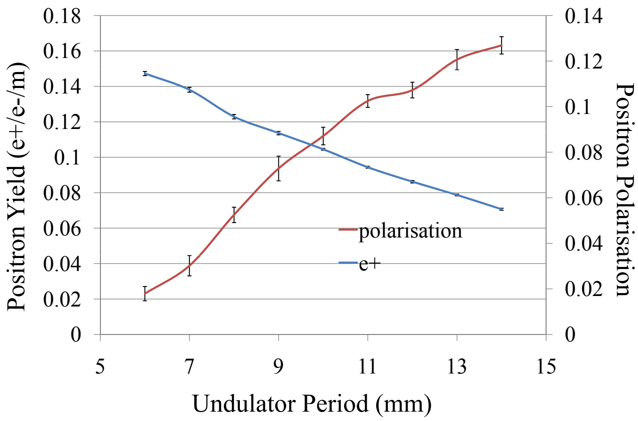

Figure 2: Positron yield and polarisation as functions of undulator period, for an electron beam energy of 350 GeV. The error bars show the statistical uncertainty in numerical modelling.

metre of undulator, and about 20% polarisation. However, reducing the electron beam energy to about 150 GeV would allow a polarisation of close to 30%, though at the cost of reducing the yield by more than a factor of two (i.e. more than doubling the required length of undulator).

Second stage The second, 3 TeV stage allows a wider choice of energy. However, Fig. 1 shows that there is a maximum positron yield when the electron energy is around 350 GeV, and that this provides a relatively low polarisation of about 10%. Depending on the specification for the polarisation, the undulator could be placed to use an electron energy anywhere between 150 GeV and 350 GeV.

Undulator Parameters

The positron yield and polarisation can be optimized, for given undulator period and field, by moving the undulator to an appropriate position along the linac. However, if we wish to use a single undulator for both stages of operation, we need to consider the optimum period and field to cover the energy range.

In general, better performance is achieved for shorter undulator periods. However, for period $\lambda_u < 10$ mm, it becomes increasingly difficult to wind the superconductor into a helix [7]. Despite this engineering limitation, we can still consider in simulations, periods from 6 mm to 14 mm.

First stage For 150 GeV electron energy, an increase in the undulator period from 6 mm to 14 mm leads to a reduction in the positron yield from 0.067 to 0.01; however, the polarisation remains roughly constant at about 30%.

Second stage In Fig. 2, we show the positron yield and polarisation as functions of undulator period, for an electron beam energy of 350 GeV. Again, shorter undulator periods lead to better performance.

For a given period, we can specify the field strength by the K (deflection) parameter:

$$K = \frac{e}{2\pi m_0 c} \cdot B \cdot \lambda_u \approx 0.934 \cdot B[T] \cdot \lambda_u[cm]. \quad (1)$$

where m_0 is the rest mass of electron, c is speed of light, λ_u is the period of undulator and B is peak field on axis. In principle, the higher the K parameter, the greater the number of photons produced by the undulator, and consequently the greater the number of positrons. If we choose (based on engineering limitations) a period of 10.5 mm, then in order to avoid quenching the superconductor, the maximum magnetic field is around 1.1 Tesla, i.e. a K parameter value of about 1. This matches the baseline design for the helical undulator in the ILC positron source.

A feasible set of parameters for the undulator in an undulator-based positron source for CLIC is shown in Table 1.

Table 1: Undulator Parameters, Assuming Variable Location

Centre of mass energy	0.5	3	TeV
Driving beam energy	150	350	GeV
Undulator period	10.5	10.5	mm
Field on axis	1.1	1.1	T
Undulator strength, K	1.1	1.1	
Active undulator length	100	40	m

FIXED UNDULATOR POSITION

Now we consider the use of different undulators in the two stages of collider operation, but at a fixed position in the linac. This means that when moving from stage 1 to stage 2, the energy of the electron beam will increase sixfold. So, if in the first stage, the undulator is located at the 150 GeV linac position, in the second stage, the electron beam energy will be 900 GeV. At this energy, assuming the undulator period and field strength shown in Table 1, the first harmonic cut-off for the photon energy will be 400 MeV, which would make design and operation of the target and capture device very difficult. One solution is to reduce the first harmonic cut-off to 10 MeV by changing the period and/or field, and use the same target and capture device.

The first harmonic of the undulator radiation is given (on-axis) by:

$$\omega_1|_{\theta=0} \approx \frac{2\gamma^2\omega_0}{1+K^2}, \quad (2)$$

where ω_0 is the circular frequency of the electron's helical orbit and γ is the Lorentz factor of the electron.

$$\omega_0 \approx \frac{2\pi c}{\lambda_u}. \quad (3)$$

We see that with fixed K, in order to keep the photon energy fixed, the undulator period needs to be increased as the square of the electron beam energy. Then, to keep the

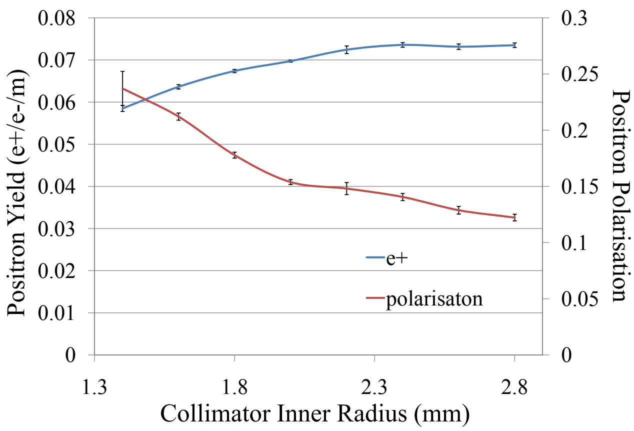

Figure 3: Positron yield and polarisation as functions of photon collimator aperture, for an electron beam energy of 350 GeV. The error bars show the statistical uncertainty in numerical modelling.

same number of photons, the total undulator length needs to be increased in proportion to the electron beam energy. Again for fixed K, the number of photons generated, N_γ, depends on the number of periods N and the period λ_u as $N_\gamma \propto N^2\lambda_u$. Therefore, if the electron beam energy is increased by a factor of 6, to keep the photon energy the same, we need to increased the period by a factor 36, and to keep the total number of photons fixed, we need to reduce the number of periods by a factor 6. Overall, the length of the undulator will increase by a factor of 6. Assuming a total length of undulator of 100 m in stage 1, 600 m will be needed in stage 2 which may be feasible, though is clearly not attractive. It is possible that a better solution may be found by relaxing the constraint of keeping undulator parameter K fixed.

Since the polarisation of the photon beam from the helical undulator depends on the angle of the photons with respect to the undulator axis, a photon collimator between the undulator and the target may also be used to control the polarisation.

First stage Without collimation, we find that the positron polarisation after the capture device will be about 30%. Without significantly reducing the positron yield (0.022 positrons per electron per metre of undulator), a photon collimator with aperture 2.4–2.6 mm will increase the positron polarisation to 40%. A polarisation of 60% may be achieved by collimation with smaller aperture, but with reduced positron yield, necessitating a longer undulator.

Second stage Fig. 3 shows the positron yield and polarisation as a function of collimator aperture, for an electron beam energy of 350 GeV. It is possible to achieve some improvement in polarisation, from 15% to 24%, at the cost of some reduction in yield, from 0.073 to 0.058. The curves flatten off for collimator apertures larger than 2.4 mm, because of the capture optics acceptance.

SUMMARY AND CONCLUSIONS

The range of proposed operating energies for CLIC presents some challenges for an undulator-based source. It is difficult to find a single location and set of parameters that will enable the source to operate effectively over the full energy range from 500 GeV to 3 TeV; however, by moving the undulator to a different location, or replacing the undulator at a fixed location, the range of working points can be accommodated.

For the 500 GeV stage, an electron beam energy of 150 GeV could be suitable. With the use of a photon collimator, high polarisation can be achieved with good yield and with reasonable undulator length. Furthermore, the source could be operated with an electron beam energy as low as 50 GeV. For the 3 TeV stage, it is possible to achieve high yield with a short undulator (40 m), although the polarization would be only about 15%.

If we assume that the undulator is kept in a fixed position, the 150 GeV electron beam energy in the first stage will increase to 900 GeV in the second stage. However, the energy and quantity of the photons can be kept fixed by increasing the undulator period, and reducing the field (keeping constant K): however, the total length of the undulator would then need to increase by a factor six. While it seems feasible to use an undulator-based positron source to cover a wide range of operating parameters for CLIC, further optimisation studies are needed to make the upgrades as easy as possible.

Optimisation of the optical matching device also needs to be considered. Here, we have assumed an AMD which maximises the yield by providing a high magnetic field at the target; however, this makes the target itself a difficult engineering problem.

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